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Projection of 21st century irrigation water requirement across the Lower Mississippi Alluvial Valley

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ABSTRACT

Lower Mississippi Alluvial Valley (LMAV) is the largest floodplain and one of the most productive agricultural regions in the United States. Irrigation is widely used in this region to improve crop production and resource use efficiency due to a mismatch between crop water requirements and precipitation timing and quantity during the growing season. In the recent decades, aquifer decline caused by groundwater withdrawals for irrigation has been recognized as a critical environmental issue threatening water security and agricultural sustainability in the LMAV. To improve agricultural water use efficiency and reduce groundwater withdrawals, it is pivotal to understand the spatiotemporal patterns of crop irrigation water requirements (IWR). In this study, we analyzed future climate changes over the LMAV cropland areas and estimated future IWR changes for major crops in the 21st century using two climate scenarios (i.e. RCP45 and RCP85) and two crop growth duration length (GDL) scenarios [i.e. Fixed GDL (GDL does not change with time) and Varied GDL (GDL changes with time)]. Results show that croplands in the LMAV would experience continuous warming, and either no significant change or a decreasing level of precipitation under the RCP45 and the RCP85. If keeping current cropland areas and cropping systems unchanged, average crop IWR by the end of the 21st century would increase by 4.2% under the RCP45 + Varied GDL scenario, 14.5% under the RCP45 + Fixed GDL scenario, 9.2% under the RCP85 + Varied GDL scenario, and 29.4% under the RCP85 + Fixed GDL scenario. The greatest increases would occur in the summer months. Aquifer levels in the LMAV, therefore, are expected to decline at an accelerated pace if no effective mitigation strategies are implemented. This study made the first attempt to reveal the spatially-explicit crop IWR and its future changes in the LMAV, which provides a scientific basis for developing management strategies that can enhance water use efficiency and improve agriculture sustainability.

1. Introduction

Lower Mississippi Alluvial Valley (LMAV) is the largest floodplain in the U.S. (Jenkins et al., 2010). It includes a part of seven states extending from southern Illinois to the Gulf of Mexico with more than 85% of the land area situated in Arkansas, Mississippi, and Louisiana. The rich alluvial soils received from sediment additions from Mississippi River support highly productive terrestrial ecosystems (Putnam et al., 1960). Bottomland forests and wetlands were once widely distributed across this region as a result of the flat terrain, poorly drained soils, and wet climate condition. At present, the LMAV becomes one of the most important agricultural regions in the U.S. for rice, soybean, corn, and cotton productions. Associated with the intensified agricultural activities, multiple environmental issues have gradually emerged, such as greenhouse gas emissions (Jenkins et al., 2010), soil erosion and nutrient leaching (Alexander et al., 2008), water quality degradation (Ouyang et al., 2014), hypoxia in the Gulf of Mexico (McIsaac et al., 2001; Rabalais et al., 2002; Turner and Rabalais, 1994), and groundwater depletion (Konikow, 2015; Ouyang et al., 2018; Reba et al., 2017; Scott et al., 1998).

At the global level, irrigated cropland represents ~20% of total cropland area, but contributes ~40% food production (Siebert et al., 2005) and ~70% freshwater withdrawals (Siebert et al., 2010). In the U.S., irrigated cropland is about 22.6 million ha (USDA, 2014), and irrigation water withdrawals account for 42% of total freshwater withdrawals (Dieter et al., 2018). Irrigation is one of the major management practices in the LMAV to maintain optimum crop growth and high crop production because the timing and quantity of precipitation

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fail to meet crop growth requirement. It is noted that the expansion of irrigated cropland has led to significant aquifer decline in the lower Mississippi River basin over recent decades (Reba et al., 2017). Largely due to irrigation water withdrawals, the Mississippi embayment of Gulf Coastal Plain aquifer shows the largest volumes of groundwater depletion in the U.S. (Konikow, 2015; Reba et al., 2017), which threatens the sustainability of water supply and agricultural production (Aeschbach-Hertig and Gleeson, 2012; Gleeson et al., 2012). To solve this problem, numerous mitigation strategies have been suggested to enhance irrigation efficiency and reduce groundwater withdrawals, such as on-farm storage pond construction (Ouyang et al., 2018) and irrigation technology improvement (Evans and Sadler, 2008; Stubbs, 2015).

To design effective strategies for lessening irrigation water use, we need a clear understanding of the spatial and temporal variations of crop irrigation water needs. In the LMAV, Massey et al. (2017) estimated the irrigation rates for major crops through a power conversion coefficient approach, and found a much higher irrigation rate in rice paddy than other crops. However, literature regarding irrigation water use in the LMAV is very limited, and it is still unclear how climate change and human management practices will affect regional crop irrigation water needs in the future. This knowledge gap restricts our ability to project future water resources availability and design appropriate strategies to maintain or enhance crop production.

Future climate changes play a critical role in affecting crop irrigation water use through altering crop evapotranspiration rate, precipitation amount, and crop growing season length (Evans and Sadler, 2008). According to general circulation model (GCM) projections, the climate warming in the 21st century is very likely to continue or even be accelerated in the Mississippi River Basin (e.g. Knutti and Sedláček, 2013; Melillo, 2014; Tao et al., 2014). In contrast, the pattern of precipitation changes in the Southeast U.S. is subject to large uncertainties (Kunkel et al., 2013). Additionally, it is not clear how the crop growing season will change in the future. Some previous studies reported that climate warming shortened crop growing season (He et al., 2015; Liu et al., 2010; Wang et al., 2013; Zhang et al., 2013); while others reported that a change in crop cultivar could extend crop growth duration and partially counteracted the impact of climate warming (Liu et al., 2012, 2010; Sacks and Kucharik, 2011).

Crop irrigation water requirement has been investigated previously by both simple crop irrigation algorithms (e.g. Döll and Siebert, 2002; Fischer et al., 2007; Shen et al., 2013; Xu et al., 2019) and sophisticated process-based crop models (e.g. Elliott et al., 2014; Konzmann et al., 2013). Of all these approaches, crop irrigation water requirement (IWR) is a simple but effective index to estimate the water quantity and depth required for optimized crop growth and yield (USDA, 1993). This index considers crop evapotranspiration and precipitation rates at daily or monthly scale, and has been extensively utilized to evaluate regional and global irrigation water requirement under historical (e.g. Döll and Siebert, 2002; Shen et al., 2013; Wriedt et al., 2009) and future climate conditions (e.g. Fischer et al., 2007; Shahid, 2011; Xu et al., 2019).

In this study, we aim to explore future climate changes and assess future crop IWR in the LMAV. We included eight sets of future climate data simulated by four GCMs under two climate scenarios (i.e., the RCP45 and the RCP85), and designed two future crop growth season length scenarios for seven major crop types. Specific objectives of this study are to (1) understand the patterns of changing temperature and precipitation in the 21st century by analyzing the downscaled and bias-corrected climate projections, (2) quantify future patterns of regional and crop-specific IWR under the impacts of climate change and cultivar change, and (3) discuss potential mitigation strategies to reduce groundwater withdrawals for irrigation while improving water/crop sustainability in the LMAV.

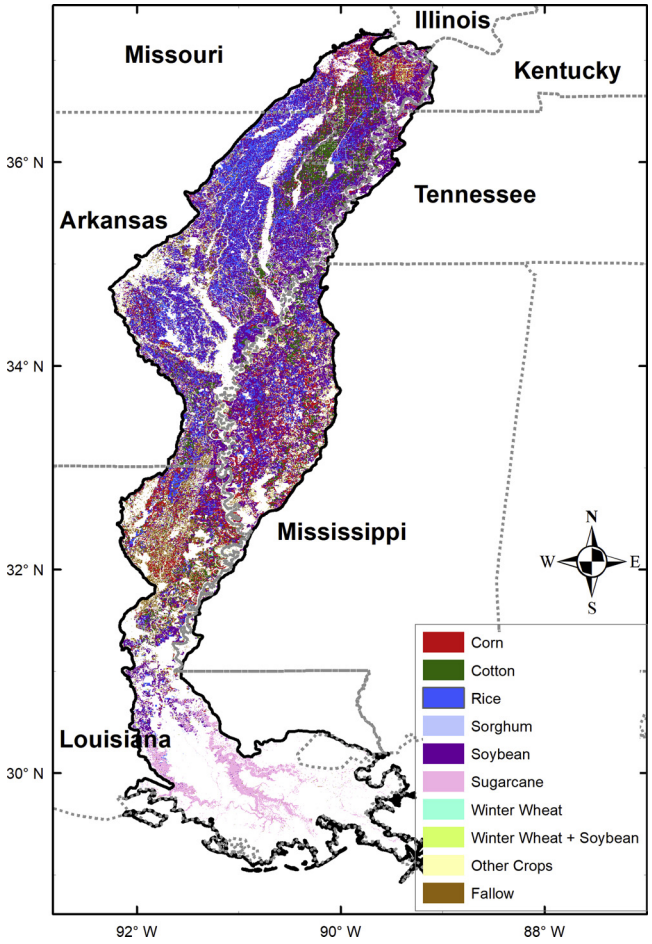

Fig. 1. Boundary of the Lower Mississippi Alluvial Valley and spatial distribution of major crops.

2. Material and methods

2.1. Study domain

The LMAV covers portions of seven states, including Illinois, Kentucky, Missouri, Tennessee, Arkansas, Mississippi, and Louisiana. The fertile alluvial soils support highly productive ecosystems (Putnam et al., 1960). Landscape in the LMAV is relatively flat. Elevation in the south is 0–20 meters, and 80–100 meters in the north, with an average of 41 m (Figure S1). In this study, we used the United States Environmental Protection Agency (EPA) Level III ecoregion (https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states) to delineate the boundary of the LMAV (Fig. 1). EPA ecoregion boundary shows that the LMAV is comprised of approximately 11.3 million ha land area. Prior to the 17th century, 8–10 million ha bottomland hardwood forests were widely distributed across this region (Stanturf et al., 2000). However, since the European settlement, a large fraction of wetlands were drained, and vegetation types were substantially changed by human activities. Currently, most of the bottomland forests have been cleared for agricultural use (King et al., 2006).

According to the Köppen-Geiger classification system (Peel et al., 2007), the LMAV is situated in a temperate rainy climate zone. During the 20 years between 1991 and 2010, average temperature is 17.6 °C, and average precipitation is 1363 mm yr^{-1} (Figure S2). Annual temperature decreases from 20 °C in the south to 15 °C in the north. Precipitation declines with distance from the Gulf of Mexico, and annual precipitation decreases from 1600 mm yr^{-1} in the south to 1200 mm

yr^{-1} in the north. Monthly temperatures are higher in summer months of June (26.1 °C), July (27.6 °C), August (27.3 °C), and September (23.9 °C) (Figure S3). The lowest monthly precipitation is in August (89 mm $month^{-1}$) and September (96 mm $month^{-1}$).

2.2. Database

2.2.1. Crop types

Cropland Data Layer (CDL) is a geo-referenced crop classification product developed based on mid-resolution satellite imageries (30 or 56 m) and ground truth data for the continental U.S., and disseminated from the United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS) (Boryan et al., 2011). This data has been widely used by scientists, policy and decision makers, and farm producers to evaluate crop yield, monitor land use change, assess disaster consequences, account regional carbon balance, etc. (e.g. Han et al., 2012; Kutz et al., 2012; Shao et al., 2010; West et al., 2010). In this study, we analyzed the CDL 2010 data at a spatial resolution of 30 m to show crop type distribution in the LMAV (Fig. 1). As indicated by this dataset, LMAV cropland (including fallow land) is ~6 million ha, accounting for 53% of the LMAV land area. We selected seven major row crops and one double cropping system to assess crop IWR. The selected row crops are corn, cotton, rice, sorghum, soybean, sugarcane, and winter wheat, and the double cropping system is winter wheat paired with soybeans (Table 1). Areas of selected crops represent ~90% of the total cropland area (including fallow land) in the LMAV. Crops with the largest cultivation areas include soybean (2.75 million ha), rice (0.96 million ha), corn (0.66 million ha), and cotton (0.56 million ha), which, respectively, represent 46%, 16.1%, 11.1%, and 9.3% of the LMAV cropland area. We further aggregated the 30-m USGS CDL data to a spatial resolution of 1/16° latitude/longitude (Fig. 2) to be consistent with climate data (section 2.2.2) for further analysis.

2.2.2. Climate data

We used two types of daily climate datasets: (1) observation-based climate and (2) model-simulated climate. First, we collected observation-based daily climate data (maximum/minimum temperature, and precipitation) during 1991–2010 from the Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States (Livneh et al., 2013) – the LIVNEH data hereinafter. This dataset was developed from ~20,000 NOAA weather station observations, and has been available from 1915 to 2011 at a spatial resolution of 1/16° latitude/longitude. We used the LIVNEH data to show contemporary climate conditions in the LMAV, and estimate the phenological heat units (PHUs) required for crops to reach maturity. Second, we collected a new statistically downscaled climate data (maximum/minimum temperature, precipitation, and wind speed) over the period of 1991–2099 simulated by four GCMs under the RCP45 and the RCP85 climatic scenarios (https://climate.northwestknowledge.net/MACA/). The four GCMs are CCSM4 (Gent et al., 2011), GFDL-ESM2G (Dunne et al., 2012), IPSL-CM5A-LR (Dufresne et al., 2013), and MIROC5 (Watanabe et al., 2010). GCM simulations had been corrected according to the observation-based LIVNEH data, and downscaled to a spatial resolution of 1/16° latitude/longitude using the method of Multivariate Adapted Constructed Analogs (MACA). Therefore, the model-simulated datasets are consistent with the observation-based LIVNEH dataset in terms of magnitude and spatial resolution. Advantages of the MACA approach and detailed procedures of the MACA downscaling and bias correction are described in Abatzoglou and Brown (2012). In total, eight sets of downscaled climate simulations (4 GCMs × 2 scenarios) were processed to evaluate the spatiotemporal patterns of crop IWR during 1991–2099.

Table 1
Areas of major crops in the Lower Mississippi Alluvial Plain in 2010.

Crops	Area (× 10^6 ha)	Percent of total crop land (%)
Corn	0.66	11.1
Cotton	0.56	9.3
Rice	0.96	16.1
Sorghum	0.04	0.9
Soybean	2.75	46
Sugarcane	0.14	2.3
Winter wheat	0.04	1.2
Double cropping (Winter wheat + Soybean)	0.16	2.6

2.3. Estimation of crop irrigation water requirement

2.3.1. Irrigation water requirement equation

Unless stated otherwise, crop IWR in this study refers to the net IWR, which is the quantity of required water for optimum crop growth and does not include water transportation loss. We used the equation in Döll and Siebert (2002) and Smith (1992) to estimate daily crop IWR (mm day^{-1}).

$$IWR = \max(0,\ Kc \times ET_0 - P_{eff}) \quad (1)$$

where ET_0 is crop-specific daily reference evapotranspiration (mm day^{-1}), computed according to the FAO56 Penman-Monteith equation (Allen et al., 1998); Kc is the crop coefficient to convert ET_0 to actual crop evapotranspiration; and P_{eff} is effective precipitation (mm day^{-1}) available for crop use and can be stored in soil.

FAO56 Penman-Monteith equation is the most widely used algorithm to quantify crop reference evapotranspiration (Pereira et al., 2015). Differences in canopy resistance, radiation reflection, crop height, canopy coverage and root depth lead to divergent evapotranspiration rates (Allen et al., 1998). Time-varying Kc was used to account for variations of these factors over different growth periods. To estimate Kc, crop growing season is divided into four phenological stages, which are Initial (S1), Canopy development (S2), Mid-season (S3), and Maturation (S4), respectively (USDA, 1993). Fig. 3 illustrates a conceptual diagram of crop phenological stages. In this study, Kc out of crop growing season was set to 0, and Kc in crop growing season was computed using the three Kc parameters [Kc at initial stage (Kc_{ini}), Kc peak value (Kc_p), and Kc at maturity (Kc_m)] in Table 2 in combination with the lengths of phenological stages (Fig. 3). Kc in mid-season was equal to Kc_p, and Kc in canopy development stage and maturation stage were computed through linear interpolation.

P_{eff} is a part of precipitation available for crop use that does not run off (Döll and Siebert, 2002). In this study, we estimated P_{eff} by following Smith (1992) and Döll and Siebert (2002),

$$P_{eff} = \begin{cases} P \times \frac{4.17 - 0.2 \times P}{4.17} & P < 8.34\,mm\ day^{-1} \\ 4.17 + 0.1 \times P & P \geq 8.34\,mm\ day^{-1} \end{cases} \quad (2)$$

where P is 10-day or 3-day average precipitation (mm day^{-1}). As soil is capable of storing precipitation for crop use in the next few days, Döll and Siebert (2002) and Smith (1992) calculated the multi-day average precipitation to represent the lag effect of high precipitation on soil moisture. 10-day average was applied for crops except rice, while 3-day period was used for rice because the soil in rice paddy is usually saturated and has low capacity to store precipitation. Döll and Siebert (2002) found that the simulated crop IWR using Eq. (1) agreed well with the independent state-level statistics in the U.S. (Solley et al., 1998), giving us more confidence in using Eq. (1) to estimate crop IWR in the LMAV. Uncertainties from this simplified algorithms of IWR and effective precipitation are discussed in Section 4.4.

2.3.2. Crop phenology

Previous studies reported that crop growing season was shortened by climate warming (e.g. He et al., 2015; Liu et al., 2010; Wang et al., 2013; Zhang et al., 2013), while some other studies found little or no

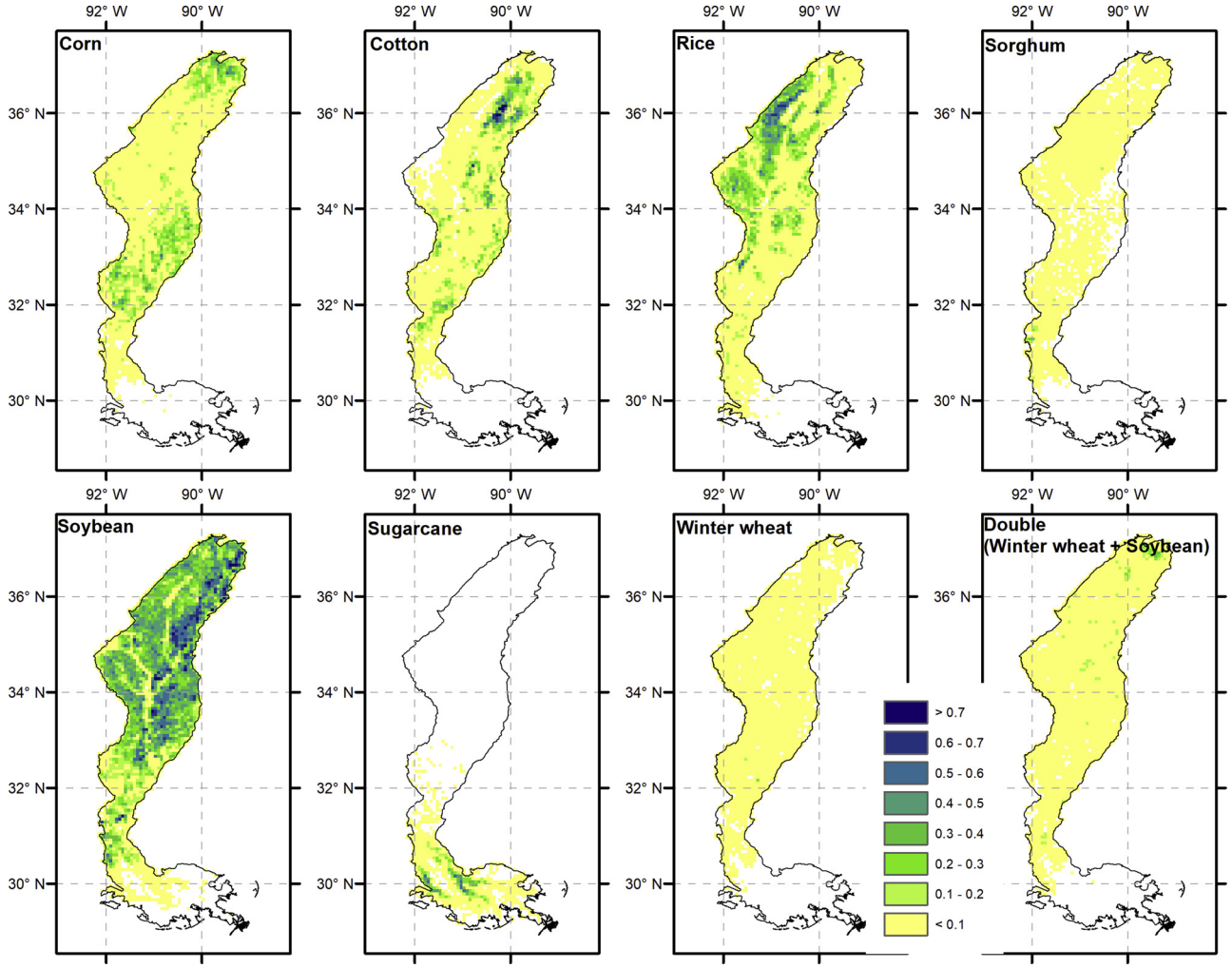

Fig. 2. Fraction of major crops in the Lower Mississippi Alluvial Valley at a spatial resolution of 1/16° latitude/longitude estimated based on USDA Cropland Data Layer (CDL) 2010.

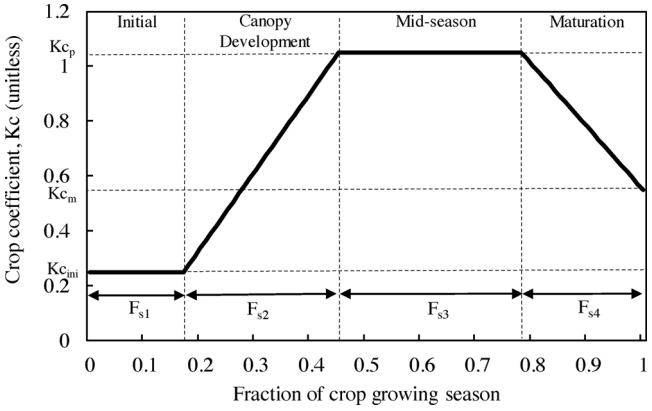

Fig. 3. Conceptual diagram of crop phenological stages and crop coefficients [Adapted from figure 2–20 in USDA (1993)].

change in crop growing season length as the improved crop cultivar lengthened vegetative growth period for biomass accumulation and counteracted the climate effect (e.g. Liu et al., 2012, 2010; Sacks and Kucharik, 2011). As it is uncertain how crop cultivars would be changed in the future, we designed two growth duration length (GDL) scenarios to estimate crop IWR. In the first scenario, we assumed crop cultivars change with time to maintain a similar growing season length as the historical level (the Fixed GDL scenario hereinafter). In the second scenario, we assumed crop cultivars do not change and GDL is determined by temperature and the accumulated phenological heat units (the Varied GDL scenario hereinafter). We assumed that time fractions of S1, S2, S3, and S4 stages to the entire growing season (F_{s1}, F_{s2}, F_{s3}, and F_{s4} in Fig. 3) do not change with time although crop GDL may change in the future.

Table 2
Time fractions of phenological stages to crop growth duration and crop coefficient parameters.

Crops	F_{s1}	F_{s2}	F_{s3}	F_{s4}	KC_{ini}	KC_p	KC_m
Corn	0.17	0.28	0.33	0.22	0.25	1.05	0.55
Cotton	0.15	0.28	0.32	0.25	0.25	1.05	0.65
Rice	0.00	0.50	0.33	0.17	1.10	1.10	0.95
Sorghum	0.16	0.26	0.33	0.25	0.25	1.00	0.50
Soybean	0.15	0.22	0.44	0.19	0.25	1.00	0.45
Sugarcane	0.09	0.25	0.48	0.18	0.55	1.05	0.6
Winter wheat	0.13	0.4	0.22	0.25	0.25	1.05	0.25

Note: F_{s1}, F_{s2}, F_{s3}, and F_{s4} are the time fractions of initial, canopy development, Mid-season, and Maturation stages to the entire growing season. KC_{ini}, KC_p, and KC_m are crop coefficients at initial stage, peak value, and at maturation stage.

Crop-specific parameters of F_{s1}, F_{s2}, F_{s3}, and F_{s4} (Table 2) were compiled from USDA report (USDA, 1993), Allen et al. (1998), and Döll and Siebert (2002). It is noted that F_{s1} for rice was set to 0 because rice initial stage is seedling nursery which happens before plantation. Rice

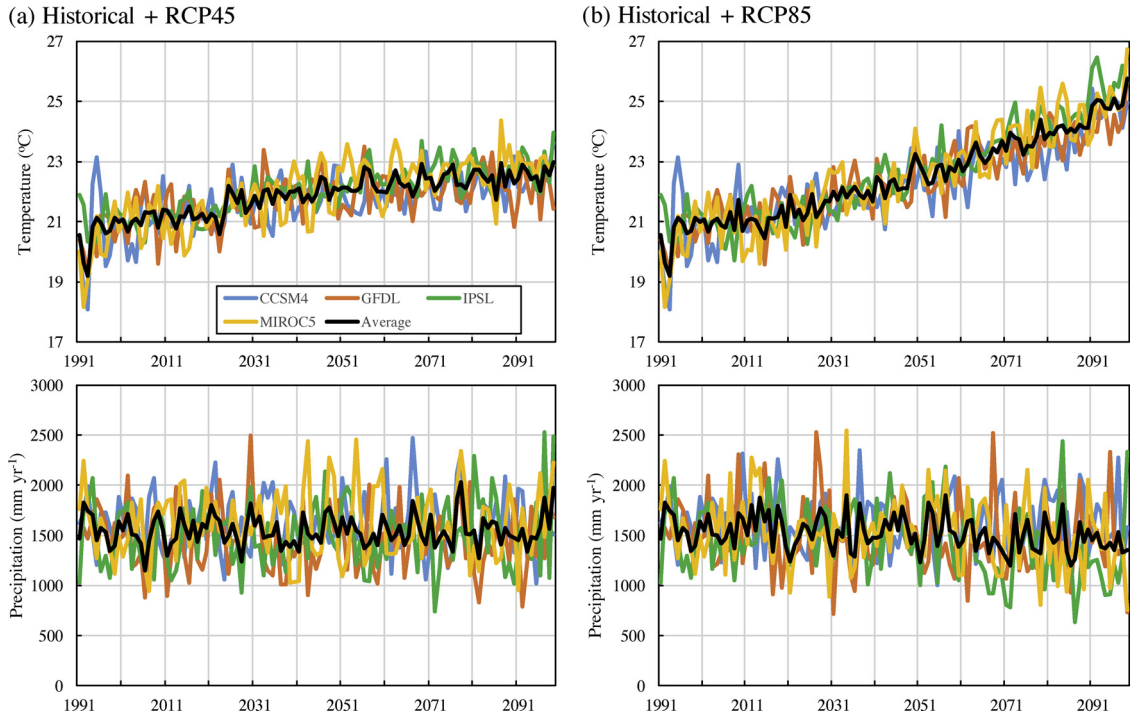

Fig. 4. Inter-annual variations of temperature (upper panel) and precipitation (lower panel) over cropland area in the Lower Mississippi Alluvial Valley from 1991 to 2099 simulated by four general circulation models (CCSM4, GFDL, IPSL, and MIROC5). (a) Historical period (1991-2005) and future period (2006–2099) under the RCP45, and (b) historical period and future period under the RCP85.

IWR in the nursery stage was not considered in this study.

2.3.2.1. Observed growth duration length based on the USDA report. USDA agricultural handbook (USDA, 2010) provides the beginning date, most active period, and end date of crop planting and harvesting for major crops at the state level. These dates were acquired from 20-year crop progress inventory data and specialists' knowledge. We used the mean day of the most active periods to denote the planting and harvesting dates for each selected crop in each state (see Figure S4 and S5). GDL was estimated by counting the days between crop planting date and harvesting date (Figure S6). It is noteworthy that sugarcane (mostly in Louisiana) has usually been cultivated over a 4-year cycle (Greenland, 2005), which is quite different from other selected field crops. For sugarcane in Louisiana, the most active planting dates were between August 18 and September 21, and the most active harvesting dates were between October 18 and December 17 of the next year (USDA, 2010). After the first harvest, sugarcane root and lower above-ground parts were left in the field and regrew to become ratoon crop. During the 4-year cycle, sugarcane is harvested three times.

2.3.2.2. Estimated growth duration length based on heat units. We used the concept of phenological heat units (PHUs) in the agricultural module of the Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2011) and the Community Land Model (CLM) (Drewniak et al., 2013) to estimate inter-annual variations of GDL for crops except sugarcane (as sugarcane harvest in the U.S. is not determined by the accumulated temperature, see explanation in the next paragraph). For each 1/16° latitude/longitude grid, total PHUs in crop growing season to reach maturity (TPHUs, °C) was calculated by the 20-year average LIVNEH daily temperature,

$$TPHUs = \sum_{i=planting\ date}^{harvesting\ date} HU_i \tag{3a}$$

$$HU_i = \max(0, \frac{Tmax_i + Tmin_i}{2} - T_{base}) \tag{3b}$$

where i is the day between planting date and harvesting date; planting and harvesting dates are from the USDA (2010) report; HU_i is daily heat unit (°C); $Tmax_i$ and $Tmin_i$ are daily maximum and minimum temperatures from the 20-year (1991–2010) average LIVNEH data; and T_{base} is base temperature required for crop growth, which is set to 5 °C as in the SWAT and CLM.

In the Varied GDL scenario, we assumed that *TPHUs* are constant. In both historical and future periods, crop is harvested when the accumulated HU_i based on the model-simulated climate reaches the *TPHUs* obtained from the 20-year average LIVNEH data. One exception is sugarcane, of which phenology and GDL had no correlation with temperature. This is mainly because sugarcane in the U.S. is harvested before physiological maturity, and the harvest date is controlled by the pre-established contract with the sugar mill (Greenland, 2005). Thus, we assumed that sugarcane GDL is fixed in both the Varied GDL and the Fixed GDL scenarios. After the harvesting dates were determined, we used parameters of F_{s1}, F_{s2}, F_{s3}, and F_{s4} in Table 2 to estimate the start and end of each phenological stage.

Some global models simulate crop planting dates by air temperature (e.g. Bondeau et al., 2007; Stehfest et al., 2007). However, this climatically determined planting date has not been widely tested and validated (Sacks et al., 2010). Thus, we assumed crop planting dates remain the same as that in the historical period for both the Varied GDL and the Fixed GDL scenarios.

3. Results

3.1. Projected temperature and precipitation changes

According to the average of four GCMs, future temperature would increase significantly (Mann-Kendall non-parametric trend test, p-value < 0.05, same hereafter) under the RCP45 and RCP85 scenarios (Fig. 4). Compared with the historical period of 1991–2005, LMAV temperature in the middle of the 21st century (MID period, 2040–2059) would increase by 1.4 °C and 1.7 °C under the RCP45 and RCP85 scenarios, respectively. However, by the end of the 21st century (LATE

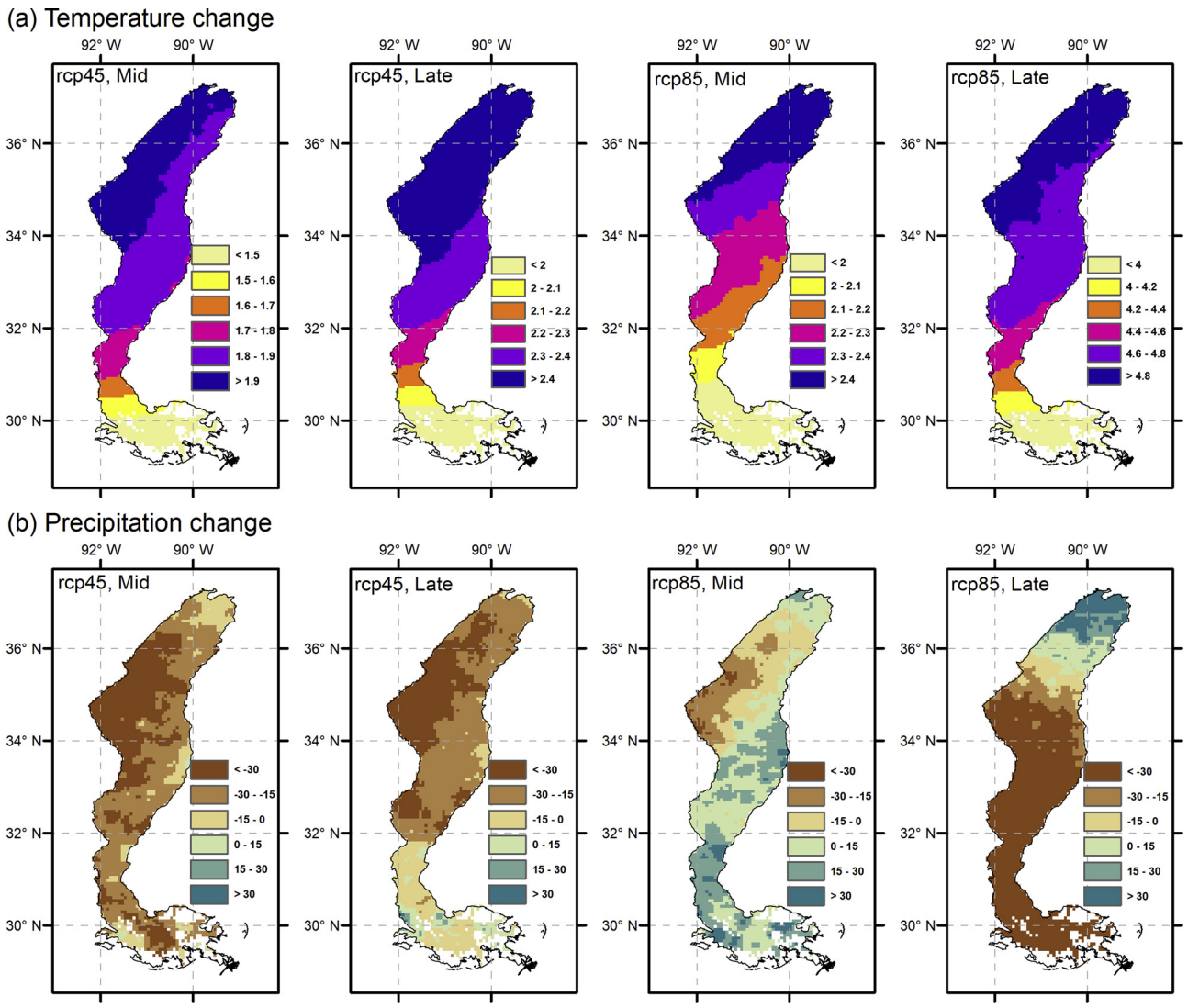

Fig. 5. Spatial patterns of changed annual temperature (a) and precipitation (b) in the MID (2040–2059) and LATE (2080–2099) periods of the 21st century relative to the historical period (1991–2005). Climate data is the average of four general circulation models.

period, 2080–2099), the increased temperature is projected to be 1.8 °C and 3.8 °C under the RCP45 and RCP85 scenarios, respectively. Spatial patterns of temperature changes show that the northern LMAV would have a higher temperature increase than that in the southern LMAV (Fig. 5).

We found that the trend in precipitation is not significant under the RCP45 scenario (p-value > 0.05) and precipitation is projected to decrease significantly under the RCP85 scenario during the period of 1991–2099 (p-value < 0.05) (Fig. 4). Compared with the historical period of 1991–2005, precipitation in the MID 21st century would decrease by 21.2 mm yr^{-1} (1.4%) under the RCP45 scenario, but increase by 13.2 mm yr^{-1} (0.8%) under the RCP85 scenario. In the LATE 21st century, precipitation would decrease by 3.1 mm yr^{-1} (0.2%) and 102.4 mm yr^{-1} (6.5%) under the RCP45 and RCP85 scenarios, respectively. The largest precipitation decrease under the RCP45 would be in the northwest of the LMAV, while the largest precipitation reduction under the RCP85 would be in the central and southern parts (Fig. 5).

Future climate change is projected to present distinct monthly variations. Under the RCP45 and the RCP85, temperature would show greater increases in spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November) than in winter (December, January, and February) (Fig. 6). For example, in the LATE 21st century of the RCP85, temperature would increase by 4.1 °C, 3.9 °C, and 3.9 °C in spring, summer, and fall, and increase by 3.2 °C in winter. Similarly, the changes in precipitation would show apparent monthly variations. Summer is projected to have the largest precipitation reduction, and fall would have the largest precipitation increase. For example, over the LATE 21st century of the RCP85, summer precipitation would decrease by 35.7 mm $month^{-1}$ (-21%), and fall precipitation would increase by 22 mm $month^{-1}$ (19.7%). As summer is the major growing season for many crops in the LMAV, a reduced summer precipitation is likely to cause an increased crop IWR.

3.2. Growth duration length

We estimated crop IWR under two GDL scenarios (i.e. the Varied GDL and the Fixed GDL). For the Fixed GDL, we used the GDL derived from the USDA report (USDA, 2010) to represent GDL over the entire study period of 1991–2099. For the Varied GDL, GDL was estimated based on the accumulated PHUs. In this scenario, GDL for all the selected crops is projected to show a continuous decline under both the RCP45 and the RCP85 (Figure S7). According to the averaged results from the four GCMs, crop GDL in the MID 21st century for the selected crops would decrease by 10–18 days under the RCP45 scenario and 14–24 days under the RCP85 scenario. Crop GDL in the LATE 21st

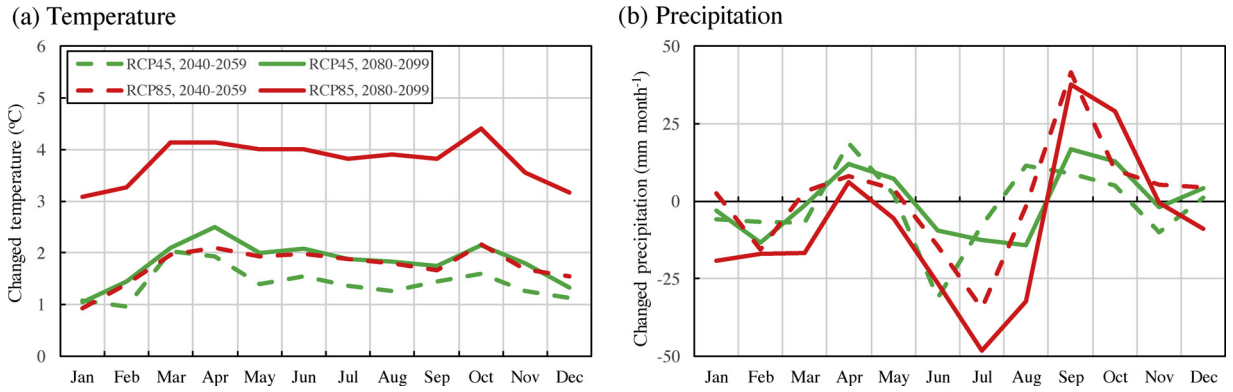
(a) Temperature
RCP45, 2040-2059
RCP45, 2080-2099
RCP85, 2040-2059
RCP85, 2080-2099
Changed temperature (°C)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
(b) Precipitation
Changed precipitation (mm month-1)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Fig. 6. Changes in monthly temperature (a) and precipitation (b) over cropland areas in the MID (2040–2059) and LATE (2080–2099) periods of the 21st century relative to the historical period (1991–2005). Climate data is the average of four general circulation models.

Table 3
Changes in crop growth duration length (days) in the Varied GDL scenario in the MID 21st century and the LATE 21st century, relative to the historical period of.1991–2005.

		RCP45					RCP85				
		CCSM4	GFDL	IPSL	MIROC5	Average	CCSM4	GFDL	IPSL	MIROC5	Average
Corn	MID	−12	−10	−11	−18	−13	−19	−15	−17	−17	−17
	LATE	−18	−13	−16	−22	−17	−30	−25	−30	−32	−29
Cotton	MID	−19	−16	−14	−24	−18	−29	−22	−21	−23	−24
	LATE	−26	−19	−19	−29	−23	−40	−34	−36	−41	−38
Rice	MID	−13	−11	−12	−18	−13	−21	−17	−18	−17	−18
	LATE	−19	−14	−16	−22	−18	−30	−26	−31	−32	−30
Sorghum	MID	−9	−9	−9	−14	−10	−15	−13	−14	−14	−14
	LATE	−13	−11	−12	−17	−14	−23	−21	−25	−27	−24
Soybean	MID	−18	−16	−13	−22	−17	−27	−21	−19	−21	−22
	LATE	−24	−19	−17	−27	−22	−37	−32	−33	−38	−35
Winter Wheat	MID	−13	−11	−13	−22	−15	−18	−12	−15	−25	−18
	LATE	−19	−12	−18	−27	−19	−39	−27	−38	−42	−36

Note: "MID": the mid-21st century (2040–2059); "LATE": the late 21st century (2080–2099).

century would be shortened by 14–23 days under the RCP45, and 24–38 days under the RCP85 (Table 3).

3.3. Reference evapotranspiration

As estimated by the FAO56 Penman-Monteith equation, future climate changes would lead to higher ET_0 under the RCP45 and the RCP85 (Fig. 7). The averaged results from the four GCMs show that annual ET_0 in the MID 21st century would increase by 62.7 mm yr^{-1} (4.6%) under the RCP45 and by 71.7 mm yr^{-1} (5.3%) under the RCP85, relative to the historical period (1991–2005). Annual ET_0 in the LATE 21st century would increase by 76 mm yr^{-1} (5.6%) under the RCP45 and by 157.1 mm yr^{-1} (11.6%) under the RCP85. Particularly, monthly ET_0 in spring and summer would show a greater increase than in fall and winter (Figure S8).

3.4. Irrigation water requirement

For the Fixed GDL scenario, crop IWR is projected to increase for all crops (Figure S9 – S17). In the Varied GDL scenario, crop IWR would increase for all crops except winter wheat (Fig. 8). We used the results in the Varied GDL and the Fixed GDL scenarios to represent the lower

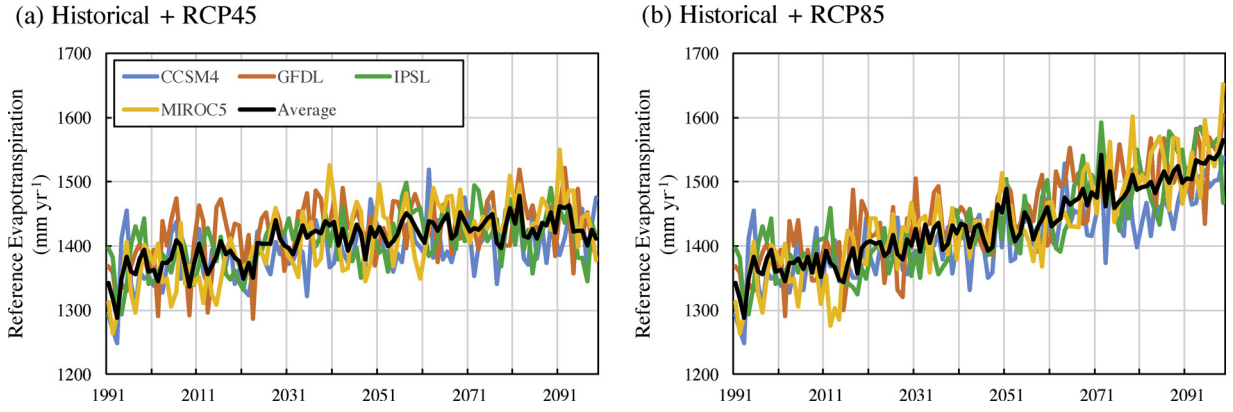

Fig. 7. Inter-annual variations of reference evapotranspiration (ET_0) over cropland areas. (a) Historical period (1991–2005) and future period (2006–2099) under the RCP45, and (b) Historical period and future period under the RCP85.

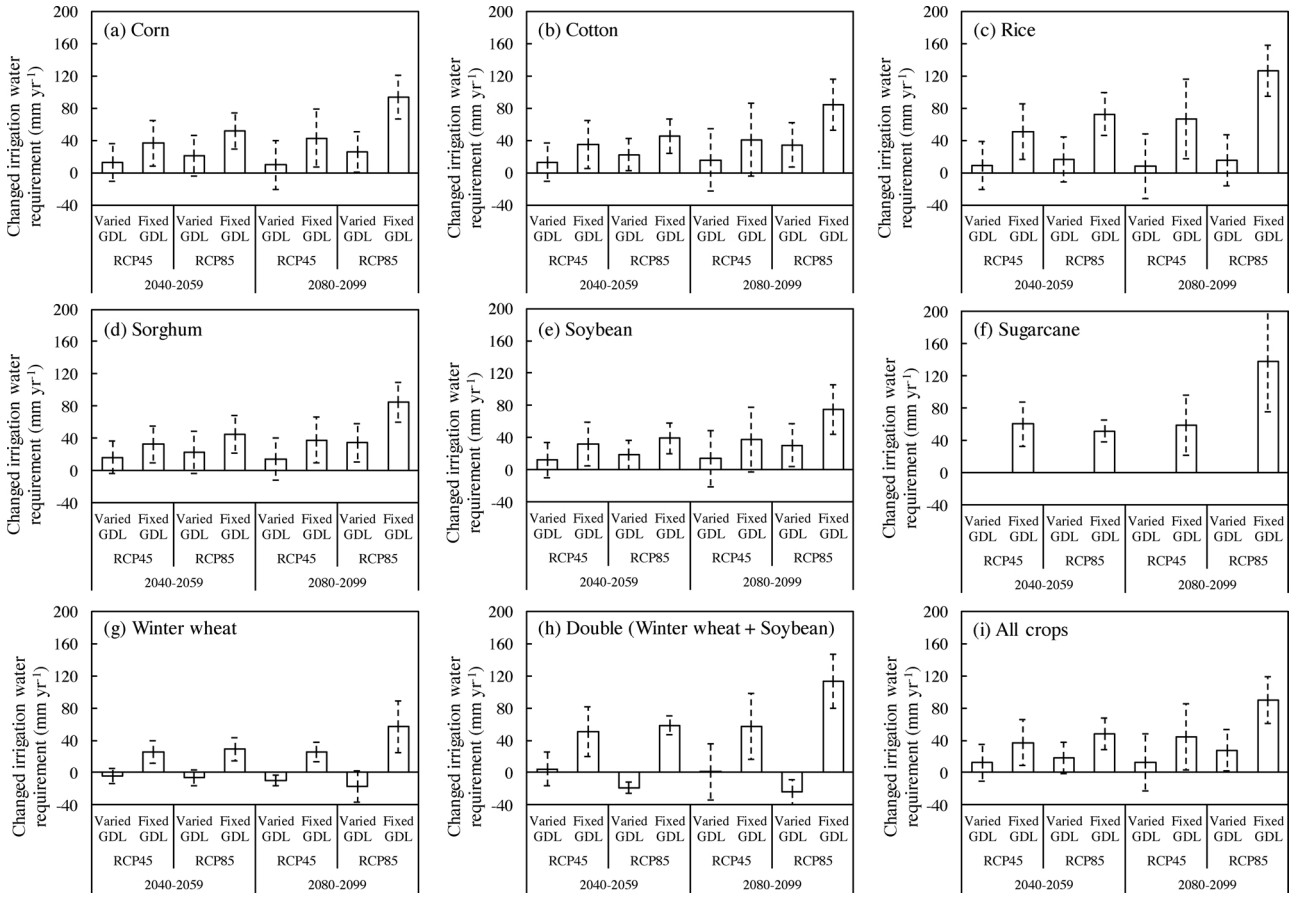

Fig. 8. Changes in irrigation water requirement (mm yr^{-1}) in the MID (2040–2059) and LATE (2080–2099) periods of the 21st century relative to the historical period (1991–2005) under two climate scenarios (the RCP45 and the RCP85) and two crop growth duration length scenarios (the Varied GDL and the Fixed GDL). Inter-annual variations of crop-explicit IWR can be found in Figure S9 - S17.

and upper boundaries of our estimates. Averaged results from four GCMs show that crop IWR under the RCP45 would increase by 12.6 ± 35 mm yr^{-1} (avg. ± 1 std. dev., same hereafter) (4.2%) in the Varied GDL scenario and 44.3 ± 41.1 mm yr^{-1} (14.5%) in the Fixed GDL scenario over the LATE 21st century, relative to the historical period (1991–2005) (Fig. 8). Under the RCP85, crop IWR would increase by 27.8 ± 25.5 mm yr^{-1} (9.2%) in the Varied GDL scenario and 89.7 ± 28.5 mm yr^{-1} (29.4%) in the Fixed GDL scenario. In the LATE 21st century, soybean IWR would increase by 5.7%–15.1% under the RCP45, and by 12.4%–30.2% under the RCP85. Rice IWR would increase by 1.7%–13.5% under the RCP45, and by 3.2%–25.5% under the RCP85. However, winter wheat IWR would diverge in changing directions between the Varied GDL scenario and the Fixed GDL scenario. During the LATE 21st century, winter wheat IWR would change between -10.1% and 23% under the RCP45 and between -17.8% and 51.4% under the RCP85.

In the historical period (1991–2005), crops in the LMAV require 16.2×10^9 (Varied GDL) – 16.3×10^9 (Fixed GDL) m^3 yr^{-1} water for irrigation use (Table 4). Under the RCP45 scenario, crop IWR in the LATE 21st century would be 16.9×10^9– 18.7×10^9 m^3 yr^{-1}, which is 4.2%–14.5% more water than in the historical period. Under the RCP85 scenario, crops in the LATE 21st century would need 17.7×10^9 – 21.1×10^9 m^3 yr^{-1} water for irrigation, which is 9.2%–29.4% more water than in the historical period. In term of total irrigation amount, soybeans require the most irrigation water as a result of its largest plantation area, accounting for ˜43% of the total amount of crop IWR in the LMAV. Rice, corn, and cotton account for approximately 29%, 11%, and 10%, respectively, of the total amount of crop IWR.

Fig. 9 shows the spatial pattern of the changes in future IWR relative to the historical period. Over the LATE 21st century, the increased IWR under the RCP45 + Fixed GDL scenario would be larger in the northern LMAV, which corresponds to a higher temperature increase and a greater precipitation reduction. For the Fixed GDL + the RCP85 scenario, the increased IWR in the LATE 21st century would be over 90 mm yr^{-1} across most cropland areas in the LMAV (except the northeast). The greatest IWR increase would be in the northwest, where rice is the major crop type. Contrasts between the upper panel and lower panel of Fig. 9 shows a lower increases in crop IWR under the Varied GDL scenario than under the Fixed GDL scenario, indicating that if crop cultivars do not change in future, the shortened crop growing season would partially offset the enhanced crop IWR.

Crop IWR in the LMAV presents distinct seasonal variations, with the highest rate during May–September (Fig. 10). For the Varied GDL scenario under the RCP45 and the RCP85, future crop IWR would increase substantially in June and July, but decrease in September and October due to the shortened crop growing season. In the LATE 21st century, crop IWR in June and July is projected to increase by 11.5 mm $month^{-1}$ and 21 mm $month^{-1}$ in the RCP45, and 28.7 mm $month^{-1}$ and 35.5 mm $month^{-1}$ in the RCP85, respectively; while crop IWR in September and October is projected to decrease by 19.9 mm $month^{-1}$ and 9 mm $month^{-1}$ in the RCP45, and 37.5 mm $month^{-1}$ and 9.5 mm $month^{-1}$ in the RCP85, respectively. For the Fixed GDL scenario under the RCP45 and the RCP85, future IWR would increase in each month of crop growing season. July and August are the months with the largest crop IWR increase. In the LATE 21st century, crop IWR in July and August is projected to increase by 11.8 mm $month^{-1}$ and 11.5 mm $month^{-1}$ in the RCP45, and 27.4 mm $month^{-1}$ and 26.2 mm $month^{-1}$ in the RCP85, respectively. The increased summer IWR could largely be

Table 4
Amount of irrigation water requirement amount ($\times 10^9$ m^3 yr^{-1}) for major crops in the Lower Mississippi Alluvial Plain.

Crop type	Fixed GDL					Varied GDL				
	Hist	RCP45, MID	RCP45, LATE	RCP85, MID	RCP85, LATE	Hist	RCP45, MID	RCP45, LATE	RCP85, MID	RCP85, LATE
Corn	1.83	2.08	2.12	2.18	2.46	1.80	1.89	1.87	1.94	1.97
Cotton	1.58	1.78	1.82	1.84	2.06	1.57	1.65	1.66	1.70	1.77
Rice	4.79	5.29	5.44	5.50	6.02	4.75	4.84	4.83	4.91	4.90
Sorghum	0.08	0.09	0.10	0.10	0.11	0.08	0.09	0.09	0.09	0.09
Soybean	6.89	7.78	7.93	7.97	8.97	6.82	7.16	7.20	7.34	7.66
Sugarcane	0.59	0.64	0.64	0.63	0.75	0.59	0.64	0.64	0.63	0.75
Winter wheat	0.05	0.06	0.06	0.06	0.07	0.04	0.04	0.04	0.04	0.04
Double	0.51	0.59	0.60	0.60	0.69	0.52	0.53	0.52	0.49	0.48
All crops	16.33	18.31	18.70	18.88	21.13	16.18	16.83	16.85	17.14	17.67

Note: GDL: growth duration length; Double: double cropping, winter wheat paring with soybean; Hist: historical period (1991–2005); "MID": the mid-21st century (2040–2059); "LATE": the late 21st century (2080–2099).

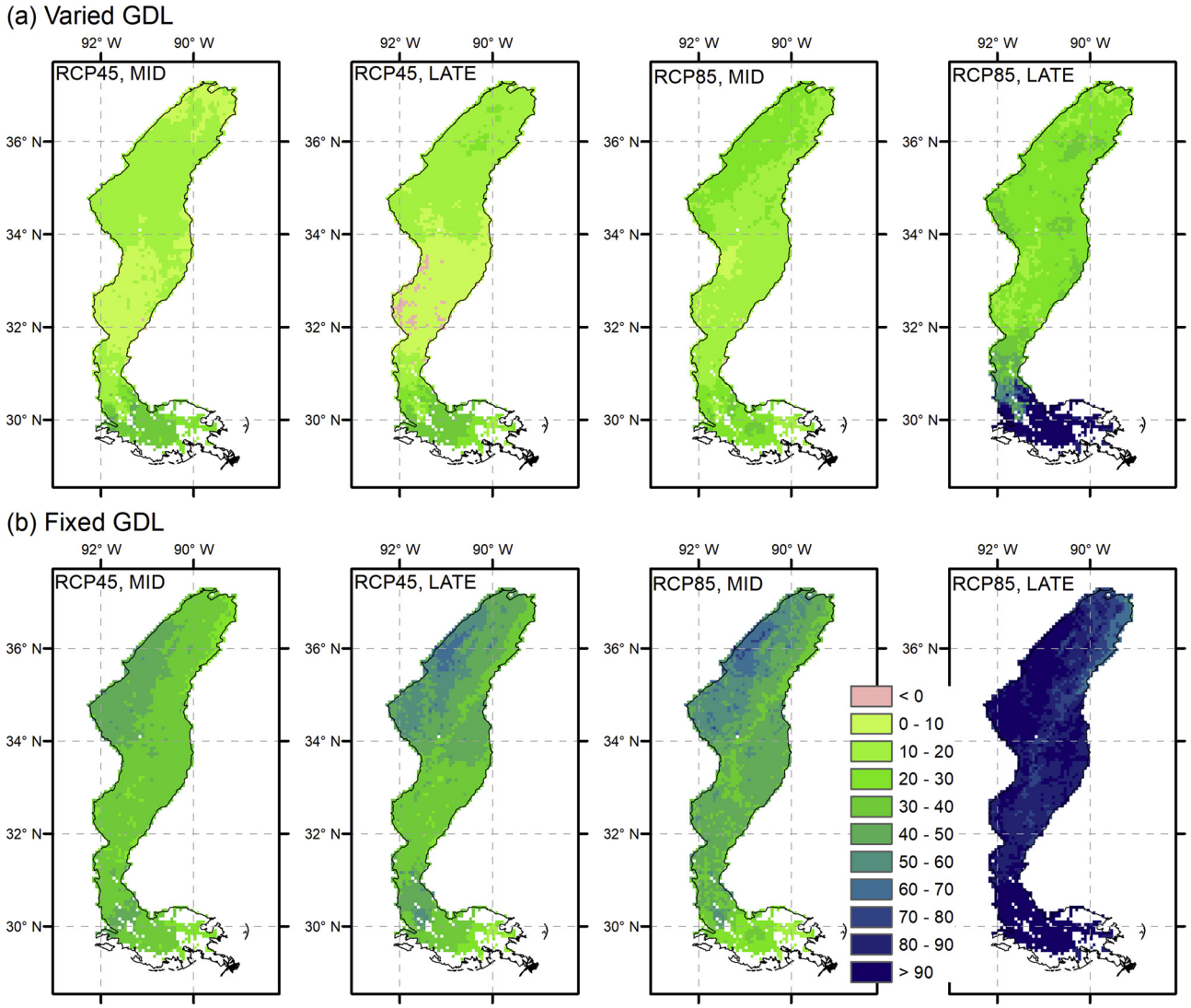

Fig. 9. Changed crop irrigation water requirement (mm yr^{-1}) under the RCP45 scenario and the RCP85 scenario in the MID (2040–2059) and LATE (2080–2099) periods of the 21st century relative to the historical period (1991–2005). (a) Varied crop growth duration length (GDL) with temperature, (b) fixed GDL at the historical level.

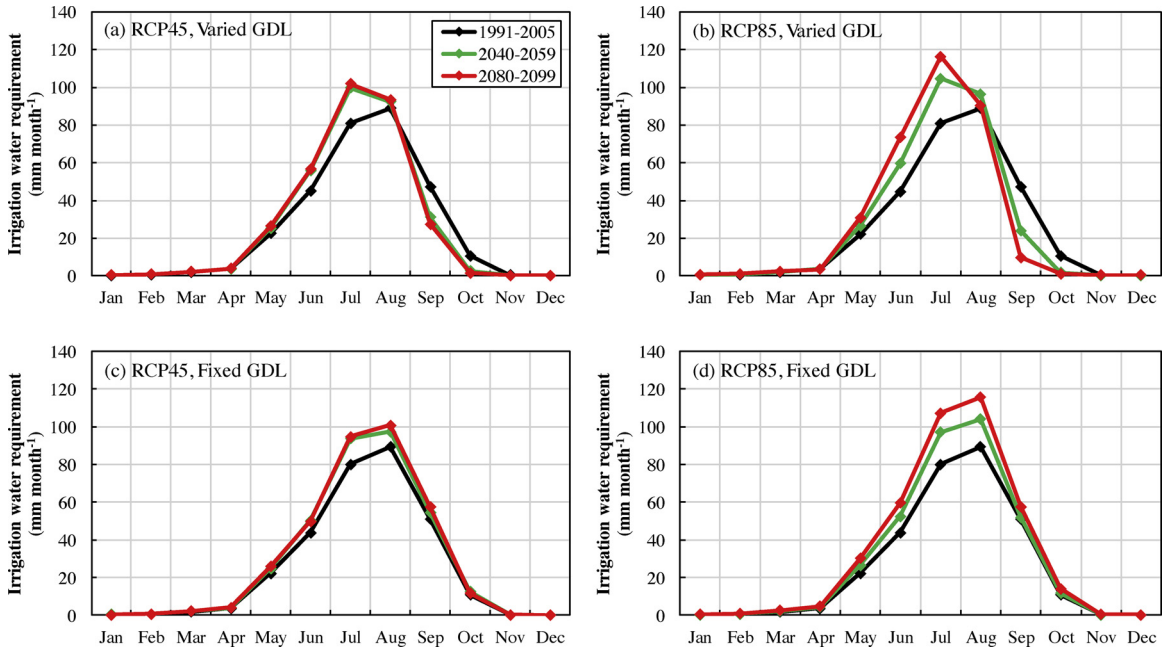
(a) RCP45, Varied GDL
(b) RCP85, Varied GDL
(c) RCP45, Fixed GDL
(d) RCP85, Fixed GDL
1991-2005
2040-2059
2080-2099
Irrigation water requirement (mm month⁻¹)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
0 20 40 60 80 100 120 140

Fig. 10. Monthly crop irrigation water requirement (mm month^{-1}) in historical period (1991–2005), the MID (2040–2059) and LATE (2080–2099) periods of the 21st century under two climate scenarios (the RCP45 and the RCP85) and two crop growth duration length scenarios (the Varied GDL and the Fixed GDL).

attributed to the increased temperature and decreased precipitation during summer months (Fig. 6).

4. Discussion

4.1. Impacts of future climate change on crop irrigation water requirement

Investigation of future changes in crop irrigation requirement has been an important research topic in the scientific community for decades. At the global level, future climate change was found to largely increase average crop IWR if mitigation strategies are not applied (Fischer et al., 2007). However, the changed crop IWR would show significant regional differences due to the spatial variations of future climate changes. For example, crop IWR in Zimbabwe was projected to increase by 17%–205% in the 2090s (Nkomozepi and Chung, 2012) and maize in Northeast China would demand more frequent irrigation (Xu et al., 2019); while climate change would not cause appreciable changes in total irrigation water use in Bangladesh rice paddy (Shahid, 2011).

Our estimated IWR for major row crops in the historical period is consistent with the observation-based estimates through a power conversion coefficient approach (Massey et al., 2017) and model-based estimates in the Mississippi Delta (Tang et al., 2018). In the LMAV, climate warming would result in large increases in crop reference evapotranspiration by the end of the 21st century (5.6% under the RCP45 and 11.6% under the RCP85). Meanwhile, summer precipitation would decrease by 21% under the RCP85. The projected increase in temperature and reduction in precipitation together would result in a significant increase in future crop IWR in this region, particularly for summer months. The high warming climate condition (the RCP85) would have a stronger influence in enhancing crop IWR than the relatively lower warming climate condition (the RCP45).

4.2. Irrigation efficiency

Gross IWR is the total water withdrawals to maintain optimum crop growth. A large fraction of water withdrawn from lakes, rivers, and aquifers is lost when water travels through canals and crop fields (Brouwer et al., 1989). Total water withdrawals, therefore, must be larger than the net IWR to cover water conveyance loss and soil evaporation loss. The term of irrigation efficiency (the ratio of net IWR to gross IWR) represents the share of irrigation water that can be utilized by crops compared to total water withdrawal (Brouwer et al., 1989; Döll and Siebert, 2002; Wisser et al., 2008). According to Döll and Siebert (2002), average irrigation efficiency is 0.6 in the U.S. with significant variations among crop types and irrigation systems. Irrigation efficiency for rice is even lower because rice needs flooding irrigation method (Döll and Siebert, 2002). If irrigation efficiency in the LMAV does not improve in the future or is maintained at ~0.6, water withdrawal for crop irrigation in the LATE 21st century would increase by $1.2 \times 10^9 - 4.2 \times 10^9$ m^3 yr^{-1} under the RCP45 and $2.5 \times 10^9 - 8.2 \times 10^9$ m^3 yr^{-1} under the RCP85 compared with the historical period.

Pressurized irrigation methods (e.g. sprinklers and micro-irrigation systems) could substantially enhance water use efficiency and reduce environmental burdens, compared to traditional gravity irrigation systems (Levidow et al., 2014). Since the 1980s, U.S. farmers have started to shift from gravity irrigation systems to pressurized irrigation systems (Stubbs, 2015). However, gravity irrigation systems now are still widely utilized over a large percentage of irrigated cropland in the LMAV. In Mississippi State for example, gravity irrigation systems are still applied over 70% of irrigated croplands (USDA 2013 Farm and Ranch Irrigation Survey, https://www.nass.usda.gov/Publications/AgCensus/2012/), compared to ~30% in western states (Stubbs, 2015). This contrast between the LMAV and western states indicates a large potential in the LMAV to reduce water loss and improve irrigation efficiency through the adoption of newer pressurized irrigation systems.

4.3. Irrigation strategies to reduce irrigation water withdrawals

Results in this study show that future climate and crop cultivar change would enhance cropland evapotranspiration and consequently irrigation water requirement. If no efficient mitigation strategies are designed and implemented, aquifer decline in the future would occur at an accelerated pace. To conserve water resources and improve agricultural sustainability in the LMAV, it is critical to reduce water withdrawals for irrigation use and improve crop production per unit water consumption. Irrigation optimization is a complicated process, which

requires the consideration of local weather, soil, crop phenological stage, water delivery and application schemes (Evans and Sadler, 2008).

Gravity irrigation (flooding) is the necessary irrigation method for rice paddy (Stubbs, 2015). Water-saving management practices in rice paddies (such as intermittent drying, less-than-full flooding, direct seeding, ground cover rice production, and scheduling of irrigation using tensiometer) have been studied previously and suggested to be applied in the field (e.g. Belder et al., 2004; Bouman et al., 2005; Bouman and Tuong, 2001; Datta et al., 2017). For crops that do not require gravity irrigation, sprinkler and micro-irrigation systems could be a better option to reduce water loss and conserve water resource in the LMAV (Stubbs, 2015). In recent years, pressurized systems in combination with GPS-based precision irrigation technologies allow irrigators to know site-specific soil condition, plant status, and the time and amount of water to be used to best match crop growth (Evans and Sadler, 2008). Then, irrigation could be applied at the right rate, right time, and right place with the help of new precision agricultural techniques. On-farm storage reservoir is another option to conserve water resources, which have been constructed in the LMAV and other regions in the world to collect rainfall and surface runoff for irrigation use (Carvajal et al., 2014; Ouyang et al., 2018). By using a pond-irrigation model, Ouyang et al. (2018) found there is sufficient surface runoff water to be collected by on-farm reservoirs for crop irrigation in the LMAV. On-farm reservoirs have large potentials to reduce groundwater withdrawals for irrigation purpose.

4.4. Cultivation strategies to reduce irrigation water withdrawals

Observation-based estimates show that irrigation water application rates in rice field are ~3 times that of other crops in the LMAV (Massey et al., 2017). Largely due the climate warming and drying, the largest crop IWR increase at the end of the 21st century would be in the northwest, where rice is widely planted (Fig. 2). Rice would consume much more water if the cultivation strategies have no improvement. To reduce rice irrigation requirement, it is necessary to improve rice cultivars. In the recent years, new rice cultivars with higher drought tolerance and water use efficiency have been developed by molecular biotechnology, which could maintain high crop yield in non-flooded conditions and require much less irrigation (Datta et al., 2017). Another option to reduce groundwater withdrawals could be the replacement of rice cultivation with other crops that require less irrigation, such as wheat, soybeans, and corn.

In the LMAV, summer has a lower precipitation rate than the other seasons (Figure S3), and summer drought would get worse in the future (Fig. 6). Early crop sowing could result in early growth and early maturity to avoid drought stress in August and September (Olesen et al., 2012). This plantation strategy could potentially reduce the IWR (Tang et al., 2018; Yau et al., 2011).

4.5. Uncertainties and caveats

In this study, we estimated crop IWR for major crops in the LMAV over historical and future periods under several climatic and growth duration length scenarios. These results could be potentially important for designing regional water conservation policies and strategies. We acknowledge uncertainties in our estimates resulting from input datasets, simplified algorithms, and assumptions. Although biases in GCM simulations have been corrected according to the observation-based data in the historical period, uncertainties still exist in climate interannual variations and future trend (Abatzoglou and Brown, 2012). For the four selected GCMs in this study, during 2080–2099, annual precipitation ranges from 1425 mm yr^{-1} (GFDL) to 1618 mm yr^{-1} (CCSM4) in the RCP45, and from 1293 mm yr^{-1} (IPSL) to 1674 mm yr^{-1} (CCSM4) in the RCP85; meanwhile, annual temperature ranges from 22.2 °C (GFDL) to 22.8 °C (MIROC5) in the RCP45, and from 24.1 °C (CCSM4) to 25 °C (IPSL) in the RCP85. Considering differences in GCM model structure, we used results from four GCMs to represent the cross-model uncertainty range, and the averaged results as our "best estimate" (Fig. 4).

Another important source of uncertainty is the simplified algorithm to calculate effective precipitation through multi-day average precipitation. Although Eq. (1) has been proved to be good enough in estimating crop IWR in the U.S. states (Döll and Siebert, 2002), this equation was designed for global application and does not consider the spatial variations of soil texture, soil water holding capacity, and topography on water runoff. Döll and Siebert (2002) reported that the estimated IWR based on Eq. (1) is comparable with inventory data in the US and Germany, while IWR was overestimated by 40% and 44% in Spain and India, and underestimated by 13% in China. Eq. (1) may lead to some uncertainties in the estimated spatial pattern of crop IWR in the LMAV. However, this uncertainty is difficult to be quantified due to the lack of inventory data in this LMAV region. Nevertheless, in the future work, spatial variations of soil and topography factors are necessary to be taken into consideration.

Future climate change in combination with socioeconomic factors and human adaptation activities would have complex influences on cropping systems in the LMAV (Howden et al., 2007; Tubiello et al., 2000). Crop phenology, growth duration, cropland area, and even crop types might be significantly different from the contemporary patterns. In this study, we considered the variations of crop growth duration under the impacts of changing climate and human activities (i.e., the Varied GDL scenarios and the Fixed GDL), but other cropping management practices were kept unchanged. In recent decades, crops were found to be planted earlier across many regions of the world (e.g. Sacks and Kucharik, 2011; Tao et al., 2006), and the locations of planted crops have shifted (Cho and McCarl, 2017). Therefore, we suggest future work of regional crop IWR to include human adaptation scenarios (e.g. changes in crop sowing dates, cropland area, and crop types).

Field experiments found that the rising ambient CO_2 concentration could reduce leaf stomatal conductance and then suppress transpiration rate at the leaf scale (e.g. Ainsworth and Rogers, 2007; Medlyn et al., 2001). However, CO_2 effect on transpiration for cops was relatively small (up to a few percents) than other vegetation types due to the aerodynamically smooth canopy (e.g. Field et al., 1995; Kruijt et al., 2008). On the contrary, some studies (Piao et al., 2006; Zhang et al., 2015; Zhu et al., 2016) found that CO_2 fertilization effect could stimulate leaf growth and leaf area, and then promote evapotranspiration rate. Rising CO_2 concentration reduces transpiration at the leaf scale through suppressing stomatal conductance, but may result in higher evapotranspiration at the canopy and landscape scales though increasing leaf area. As the mechanism of rising CO_2 influences on evapotranspiration has not been well understood yet, this study did not include CO_2 impacts on crop IWR.

5. Conclusions

Aquifer decline due to groundwater withdrawals for agricultural use is one prominent environment issue in the Lower Mississippi Alluvial Valley. This study made the first attempt to estimate spatial patterns of crop irrigation water requirement (IWR) and its future trend over the LMAV under climate change and growth duration length scenarios. We found that temperature in the LMAV increases continuously over this region during the 21st century, and summer drought would be aggravated as a result of reduced precipitation and increased temperature. When keeping current crop planting area and sowing date unchanged, regional crop IWR would show considerable increases ranging from 4.2% to 14.5% under the RCP45 and from 9.2% to 29.4% under the RCP85, respectively, by the end of the 21st century. We discussed uncertainties regarding climate projections and the simplified IWR algorithm, and called for future research to consider local soil related parameters, socioeconomic factors, and the changes in cultivation

strategies. Nevertheless, this study gives an insight into agricultural water use as influenced by future climate conditions. Analysis of IWR for major crops provides a scientific basis for designing management strategies to improve water and agriculture sustainability in the LMAV.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2019.02.033.

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